COMPTON OBSERVATORY OSSE STUDIES OF SUPERNOVAE AND NOVAE

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ABSTRACT

A primary objective of the Compton Observatory is the direct study of explosive nucleosynthesis in supernovae and classical novae. We have been fortunate in that three rare events have coincided, relatively speaking, with the Compton Observatory launch. Supernova 1987A, roughly a once per century event, was only 4 years old at launch and so the γ-ray flux from ^{57}Co decay was not much past its peak value. Supernova 1991T, a SN Ia which exploded within a few days of launch, is a once in a decade event. It offers as good a chance as we could reasonably expect to detect the ^{56}Ni and ^{56}Co decays which are supposed to be responsible for the impressive SN Ia display. Nova Cygni 1992, also a once in a decade event, might be our best chance to detect γ-rays from ^{22}Na, a unique nucleosynthesis byproduct of the explosive hydrogen burning thought to power classical novae.

The OSSE has detected 122 keV line and Compton scattered continuum photons from ^{57}Co decay in SN 1987A. The total flux of 9×10^{-5} cm^{-2} s^{-1}corresponds to a ^{57}Ni/^{56}Ni production of 1.5 ± 0.5 relative to solar Fe, which is in conflict with previous interpretations of optical and infrared data. OSSE and COMPTEL upper limits on ^{56}Co γ-ray lines from SN 1991T at 3-4 $\times 10^{-5}$ cm^{-2} s^{-1}are not in conflict with published models of SNIa at distances $\geq$10 Mpc. However if those models are correct, the distance must be $\leq$10 Mpc to give the observed optical luminosity, and are then in conflict with the γ-ray limits. The OSSE upper limit from N Cyg 1992 near 10^{-4} cm^{-2} s^{-1}at 1.275 MeV corresponds to an ejected ^{22}Na mass of 8×10^{-8} M$_\odot$ at a distance of 1.5 kpc.

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I. INTRODUCTION

The prospect of detection of short-lived radioactivity just following explosive events has been a cornerstone of astrophysical γ-ray spectroscopy since its beginning. The best hope, ^{56}Co in supernovae,[1] was realized first, somewhat surprisingly, in the Type II supernova SN 1987A.[2] We looked forward to the Compton Observatory, still awaiting the first detections of radioactivity in a Type Ia supernova, which should be intrinsically much brighter, and in a classical nova,[3] which are much more frequent and therefore likely to be very nearby. The Compton Observatory launch was just soon enough that we still hoped to be able to detect ^{57}Co in SN 1987A, and to measure the mass of that isotope ejected. This would for the first time allow us to determine the ratio of abundances of two isotopes produced in the deepest, highest temperature layers ejected.

II. OSSE OBSERVATIONS OF SN 1987A

Details of two OSSE observations[4] of SN 1987A and their interpretation[5] have been recently reported. Here we summarize the important features. Two 2-week averages of OSSE difference spectra are shown in Figure 1. The first observation began on July 25 1991 (1613 days after the explosion), the second on Jan 10 1992 (1768 days). Each of these spectra was fit with a model, consisting of an exponential continuum plus a ^{57}Co template, convolved with the OSSE instrument response. The template is derived from a supernova model evolved to this time and includes the 122 and 136 keV lines plus a Compton-scattered continuum. In the fit shown the model is based on the model 10HMM of Pinto and Woosley[6] which has roughly equal numbers of photons in the 122 keV line and in its Compton-scattered continuum at these times.

Both observations show an excess consistent with this template, but atop very different continua. The flux in the template, lines plus continuum, is $(9.0 \pm 2.2) \times 10^{-5}$ for the first observation, and essentially the same, although with a larger uncertainty, for the second observation. For a variety of continuum models and supernova templates, the best-fit value of the flux varies by less than the 1σ statistical uncertainty. Fitting the 122 keV line only, without its scattered continuum, plus an exponential continuum yields a line flux consistent with one-half that measured for the template. We have interpreted this as a detection of ^{57}Co in the SN 1987A ejecta.

In the model of Pinto and Woosley, as in all previously published models of the ejecta of SN 1987A, essentially all ($\simeq$98%) of the ^{57}Co decay photons escape at these late times, either directly in the lines or after very few scatters. Assuming this is correct, we can convert the flux into the ejected mass of ^{57}Co, which is 2.7×10^{-3} $M_\odot$ extrapolated back to t=0, assuming a distance of 50 kpc. Compared to the ^{56}Co mass of 0.075 $M_\odot$ inferred from the early UVOIR light curve, the production ratio of the parents, $X(^{57}Ni)/X(^{56}Ni)$, is 1.4 ± 0.35 times the

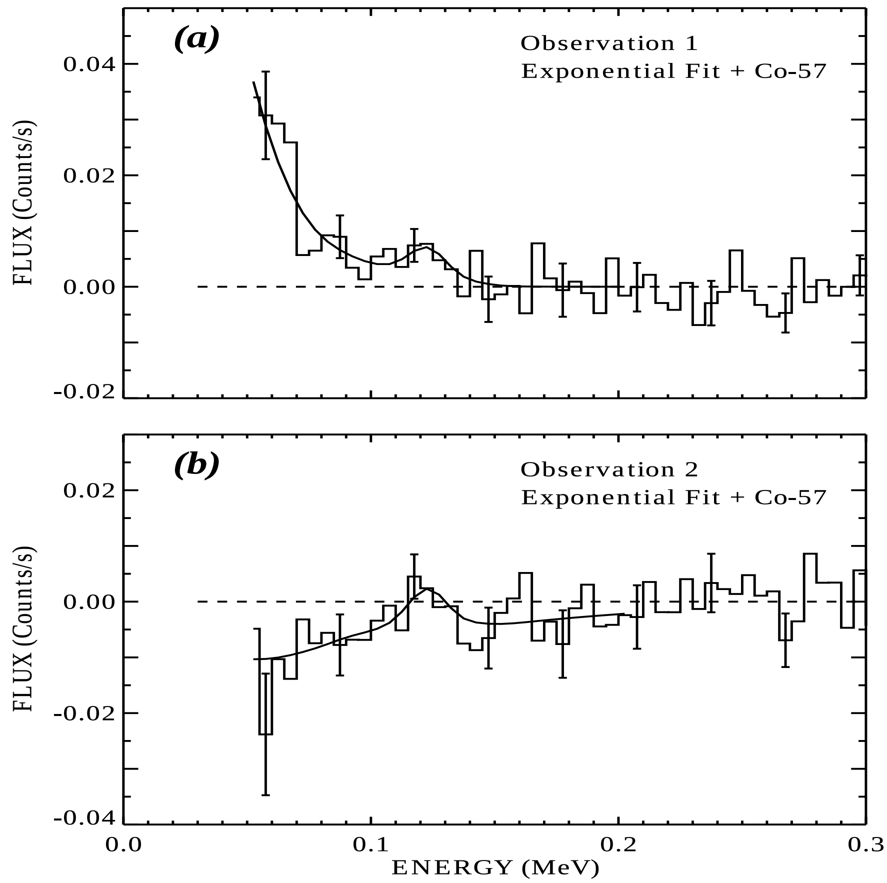

Figure 1: *The mean difference spectra for SN 1987A for the two-week viewing periods (a) No. 6 and (b) No. 17. The solid lines are the best-fit exponential continua plus* ^{57}*Co line and continuum template from model 10HMM.*

solar ratio of the daughters, (^{57}Fe)/(^{56}Fe)$_\odot$. This measurement is inconsistent with earlier inferences[7,8] that this production ratio was five times the solar value to explain the late optical/infrared luminosity in the context of the same supernova model, 10HMM.

The OSSE flux and the ground-based measurements can be reconciled with a 57/56 production ratio roughly twice the solar value *and* a supernova model which is thicker to ^{57}Co γ-rays than published models. The thicker supernova, probably a result of lower expansion velocity in the inner ejecta, would yield a lower escaping hard flux per ^{57}Co nucleus because of increased photoelectric absorption, and would have a larger fraction of the ^{57}Co power thermalized (roughly 40% at the OSSE epoch rather that 20% in, e.g.,10HMM).

However, the late-time optical/infrared luminosity is not necessarily derived entirely from ^{57}Co. Other power sources, each of which, except for the last, should be present at some level include

- Delayed release of a small fraction of the earlier large power from ^{56}Co.
- Conversion of a fraction ($\simeq 10^{-13}$ s^{-1}) of the mechanical energy of the ejecta into infrared emission.
- Other radioactivity, e. g.,^{44}Ti.
- Accretion onto or rotational energy extracted from a compact remnant.

The first effect should exist because the processes between γ-ray emission and optical escape – Compton scattering, then electron energy loss (via ionization), and subsequent recombination – have inherent delays. The most important is probably recombination, because the rapidly declining density in the ejecta causes the recombination time to grow progressively longer, delaying the release of the power.[5]

The second source, mechanical energy is available only if the ejecta interact with external material. Even the blue supergiant wind, if it blew at 2×10^{-6} $M_\odot$ /yr at 500 km/s prior to the explosion could cause significant dissipation. The ejecta, at 10^4 km/s, is sweeping up this wind at 4×10^{-5} $M_\odot$ /yr, and conservation of momentum demands that $\simeq 10^{39}$ erg/s is being dissipated. If 10% of this is emitted as light, all the luminosity in excess of ^{56}Co power can be accounted for. The rest of this dissipation luminosity might be detectable in another band (e. g.,radio, x-ray), or might go into PdV work.

As for the last two effects in the list, we doubt, based on straightforward nucleosynthesis arguments,[9] that ^{44}Ti is a dominant contributor to the luminosity, and we find no conclusive evidence for a contribution from a compact object. However, we can not rule out that the soft continuum we detect in the first observation comes from within SN 1987A.

III. OSSE OBSERVATIONS OF SN 1991T

Prior to SN 1987A, it was generally considered that a Type Ia supernovae would yield the first detection of these γ-rays, because it is thought that the energy of these events is entirely thermonuclear in origin.[10] The Type Ia light curve is supposed to be powered by ^{56}Ni decay initially and later ^{56}Co. This is the result of the thermonuclear disruption of a white dwarf near the Chandrasekhar mass, a large fraction of which is converted to ^{56}Ni. Calculations indicate that 0.5–1.0 $M_\odot$ of ^{56}Ni is ejected, depending on the nature of the burning, which remains uncertain.[11–15] In addition to the large mass of ^{56}Ni, very large expansion velocities are expected and observed in Type Ia supernova, so they become thin to γ-rays in a matter of months, before significant decay.

Supernova 1991T was discovered on April 13 1991[16] in NGC 4527, a spiral galaxy on the edge of the Virgo cluster. Its premaximum spectrum, which lacked lines of intermediate mass elements, was unusual for a Type Ia supernova, but its

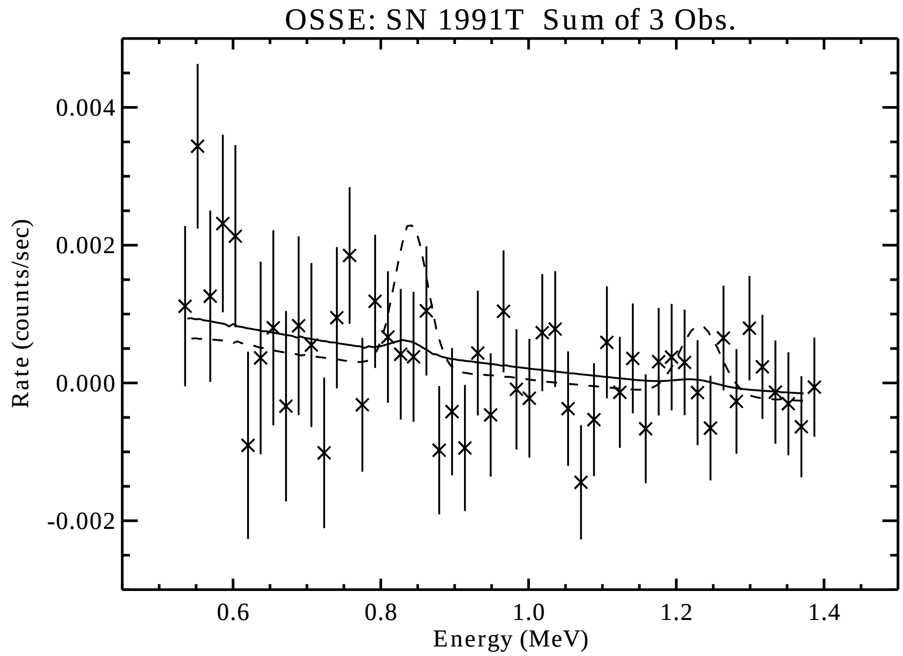

Figure 2: *The mean difference spectra for SN 1991T for all three viewing periods, all with equal weights. The solid line shows the best-fit power-law continuum plus 847 and 1238 keV lines with relative amplitudes equal to the laboratory branching ratio. The dashed line shows the same model but is fit with the 847 keV flux fixed at* $5{\times}10^{-5}$ cm^{-2} s^{-1}.

postmaximum spectrum and its light curves were quite similar to normal Type Ia's throughout.[17,18] SN 1991T peaked at about V=11.5 on about April 30 1991,[18] making it the brightest SNIa since SN 1972E.

The Compton Observatory, launched only a week before the SN 1991T discovery, was thus provided with an opportunity to test the idea of SNIa's as thermonuclear explosions. By chance the OSSE team happened to contact supernova observers just hours after the discovery. With much cooperation from the Compton Observatory flight operations team and among the 4 experiments, plans were quickly made to observe SN 1991T as the third target of the observatory. The spacecraft axis was pointed toward the supernova during the periods June 15–29 1991 and October 3–17, so both the OSSE and the COMPTEL experiment could observe it. The OSSE was also able to observe SN 1991T as a “secondary” target during August 22 – September 5 1991.

The OSSE has good sensitivity for the two strongest lines of ^{56}Co decay at 847 keV and 1238 keV. Standard OSSE analyses techniques[19] were applied to the data from all three viewing periods, and a mean difference spectrum was obtained for each. Each spectrum shows evidence for excess low-energy continuum photons from the source location. We presume these come from the quasar 3C 273 which is only 1.4 degrees from SN 1991T. We find no evidence for either line in any

of the three spectra. Figure 2 shows a simple live-time weighted mean of the three difference spectra. The solid curve is the best-fit of a model consisting of a power-law continuum plus the two lines where the ratio of the line amplitudes is fixed at the laboratory value. Also shown for illustration, as the dashed curve, is the fit when the flux in the 847 keV line is fixed at 5.0×10^{-5} cm^{-2} s^{-1}. That the flux is this high is statistically very implausible.

To draw the firmest conclusions from these combined observations, we really need to appeal to supernova models, because the fluxes are expected to vary with time, as is the ratio of the fluxes of the two lines. However, for no reasonable model is the upper limit on the 847 keV flux in the first observation very different from this simple determination, and in all cases we have tested it is $\leq 5 \times 10^{-5}$ cm^{-2} s^{-1}. Formally, 99.5% confidence upper limits, quoted for the 847 keV line flux in the first observation, vary from 3.0×10^{-5} cm^{-2} s^{-1}to 4.0×10^{-5} cm^{-2} s^{-1}. Similar limits are obtained from the COMPTEL observations during each of two observing periods (Lichti et al., this volume).

The probability of detecting the γ-ray lines from ^{56}Co decay depends mainly on the mass of ^{56}Ni produced and on the distance to the supernova. The distance to NGC 4527 is uncertain, even relative to the uncertain Virgo cluster center distance.[20] SN 1991T was somewhat brighter at maximum than the typical Virgo Cluster Type Ia supernovae (V=12.0, corrected for extinction and distance from the cluster center;[21,22]). This could be because it had a peak luminosity typical of other SNIa but is somewhat closer,[18] or because it was anomalously luminous and at nearly the same distance as the cluster center.[17] Significant extinction would require even smaller distance or higher luminosity. Regardless of these uncertainties, we expect the γ-ray line flux also to be larger than for typical Virgo cluster SNIa. However, we do not know those fluxes are, because we do not have any entirely successful model and we do not know the distance to Virgo. Still, any theoretical model is safe from the contradiction by this upper limit as long as the distance can be large enough. However, as pointed out by Arnett[23] both optical and γ-ray fluxes scale the same way with distance and approximately the same way with ^{56}Ni mass, so the ratio of γ-ray to optical flux at their respective peaks should be roughly constant for Type Ia supernovae.

A pertinent question is then: are any models consistent with a Type Ia supernova being this bright optically but with γ-line fluxes this low? Figure 3 illustrates this relationship. It shows the peak 847 keV flux versus the extinction-corrected blue magnitude at maximum. Although we do not know exactly when the peak γ-ray flux should occur, the flux at the times of our first two measurements, at least, should be very near the peak. Shown in Figure 3 are two lines of varying distance for fixed combinations of γ-ray flux/blue magnitude. One is based on an analytic description,[23,24] another on model N21 of Khokhlov.[14,25,26] The latter model is shown as a point at distance 13.5 Mpc, which has been listed for NGC 4527.[27] Also shown at this distance is the model W7,[11] which, although it has a much lower ^{56}Ni mass and is fainter, because it lies so close to the line for model

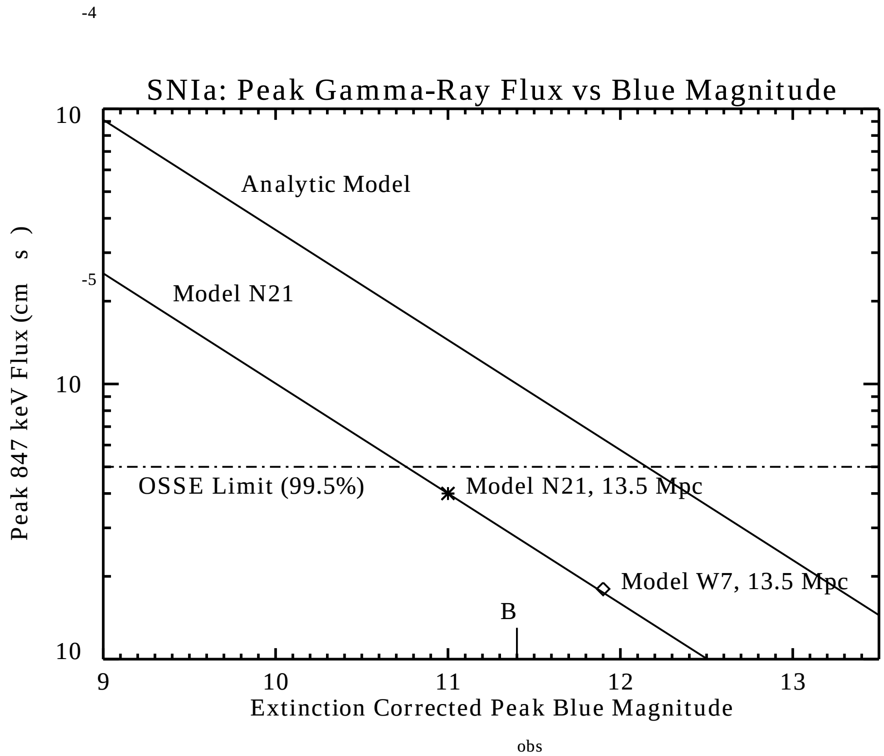

Figure 3: *The peak 847 keV flux versus peak intrinsic blue magnitude for various supernova models. Solid lines: an analytic description*[24]*, and model N21* [14] *at varying distances. Points are for N21 and model W7* [11] *at distance 13.5 Mpc.*

N21, demonstrates the validity of Arnett's idea if not his numerical result.

We can use the optical observations to determine the distance and therefore predict the peak γ-ray flux for a given model. For example, the model N21, if at a distance such that at maximum B=11.4, predicts a peak 847 keV flux of 2.8×10^{-5} cm^{-2} s^{-1}. This is consistent with the OSSE data at the 7% level of confidence. Model W7 predicts very nearly the same flux for B=11.4, but it would be at a smaller distance. The analytic model shown clearly overestimates the γ-ray line flux, and several of its assumptions are brought into question.

Significant reddening and extinction would imply that a given model should be placed at a still smaller distance, with a higher γ-ray flux, to give the observed peak B magnitude. Filipenko et al.[17] estimate extinction as high as 0.7 mag, but settle on 0.4 mag as a more probable value. Then B_{max}=11.0 mag intrinsically , and we expect the 847 keV line flux to be 4.0×10^{-5} cm^{-2} s^{-1}for either model N21 or W7. This is ruled out at the 97% level of confidence. Ruiz-Lapuente et al.[28] find $\simeq$ 1.0 mag of extinction, which implies B_{max} =10.4 and predicts $F_{max}(847)=7\times10^{-5}$ cm^{-2} s^{-1}– well above our current limit.

It is unlikely that current Type Ia models can satisfy both the optical and γ-ray measurements of SN 1991T. However, the conflict is not great enough that we can rule out the basic thermonuclear explosion paradigm. Models which more efficiently convert the decay power into optical luminosity at maximum, possibly

by storing for a short time the large premaximum ^{56}Ni decay power, can probably be developed.

IV. Nova Cygni 1992

N Cyg 1992 was discovered[29] on February 19, and reached visual magnitude V$\simeq$4 on 29 February. As this was the brightest classical nova since 1975 and likely to be relatively close, we decided to observe it with the OSSE, and did so from 5–20 March 1992. The most likely detectable radioactive byproducts of the thermonuclear explosion at that time were ^{7}Be ($\tau_{1/2}$=53 days; E_γ=478 keV in 10% of decays) and ^{22}Na ($\tau_{1/2}$=2.6 yr; E_γ=1275 keV). The prospects for detecting ^{22}Na were improved by observations that the ejecta of N Cyg 1992 were highly enriched in neon,[30,31] the seed of ^{22}Na production.

Standard analysis techniques were applied to the OSSE data, however very restrictive screening was performed. This was needed because the Compton Observatory tape recorder errors were at a very high rate at that time. Useable data were greatly reduced (less than one-half the data are included here), especially during the last week of these observations.

Figure 4 shows the mean difference spectrum for 5–20 March. We find no evidence for any line emission, including the two mentioned above and the 511 keV line which should accompany the 1275 keV line because positrons are emitted in 92% of ^{22}Na decays. Our 99.5% confidence upper limit on 1275 keV emission, assuming also that the 511 keV line flux is 0.5 of that at 1275 keV (i.e.,that the positronium fraction is $\geq$90%) is 1.3×10^{-4} cm^{-2} s^{-1}. The 99.5% confidence upper limit on 478 keV line emission is 1.2×10^{-4} cm^{-2} s^{-1}. The limits might ultimately be somewhat lower if all the data can be corrected for tape recorder errors.

Assuming that the ejecta are thin by late March, and assuming a distance to the nova, we can convert these flux limits to limits on the ejected masses of the radioactive nuclei. The first assumption is valid if ejection velocities are $\geq$100 km/s, even if as much as 10^{-4} $M_\odot$ of matter are ejected. Based on the decline of the light curve we estimate that the distance is in the range 1 to 3 kpc. For illustration, we assume a distance of 1.5 kpc in the following. Our limit corresponds to an ejected mass of ^{22}Na of $\leq 8\times10^{-8}$ $M_\odot$. This is less than given by some models, which have ^{22}Na mass-fractions of 10^{-3} (see Starrfield et al., this volume), if the ejected mass is 10^{-4} $M_\odot$. However, those models do not eject so much total mass and might not be appropriate to slow or moderately-slow classical novae (such as N Cyg 1992). If significant ^{22}Na is produced but not ejected explosively, it might be subsequently ejected in wind-driven mass-loss, in which case it might have been thick to γ-rays during our observation. This possibility and the poor data quality argue for another observation of N Cyg 1992 in the next year or two. Our 478 keV flux limit corresponds to 1.9×10^{-8} $M_\odot$ of ^{7}Be ejected at t=0. This is about the most one expects from a nova,[32] but the uncertainties in production make the upper limit much less interesting than a

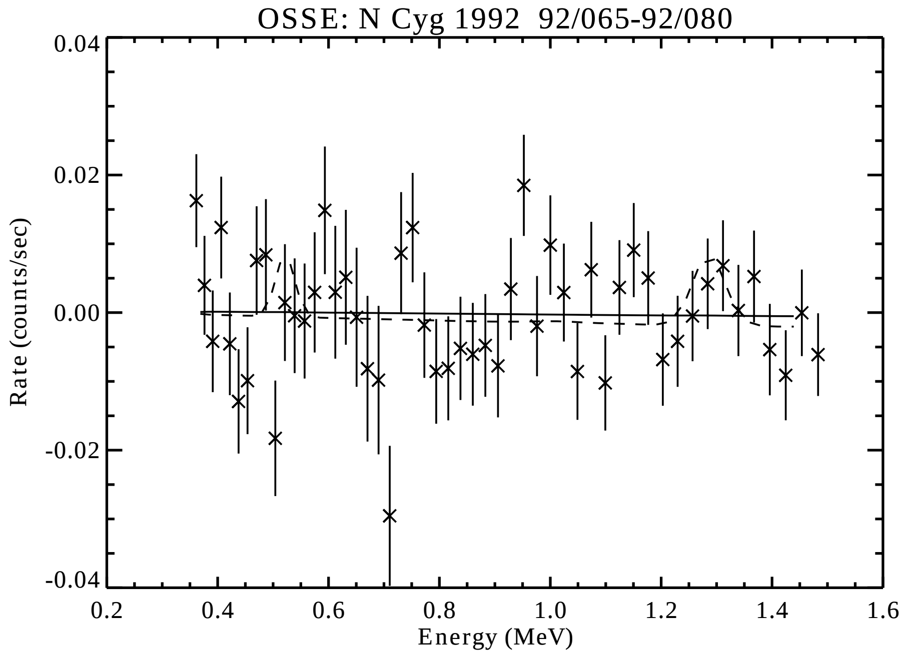

Figure 4: *The mean difference spectrum for N Cyg 1992 for the period 5–20 March 1992. The dashed line shows how a line flux of 10^{-4} cm^{-2} s^{-1} at 1275 keV and 1/2 that at 511 keV would appear.*

detection would have been.

We have been very fortunate indeed to have such an interesting observation of a Type II supernova, SN 1987A; SN 1991T was tantalizingly close to the distance where we must be able to detect current Type Ia models, but is not inconsistent with them; and N Cyg 1992, a reasonably good chance to confirm nova ^{22}Na production, might yet be detected.

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